APJ LETTERS ACCEPTED
Preprint typeset using LATEX style emulateapj v. 10/09/06

THE IDENTIFICATION OF BHB STARS USING *GALEX* AND OTHER PHOTOMETRY

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ApJ Letters accepted

ABSTRACT

Halo samples that have no kinematic bias have been successfully isolated by photometric observations. We show that the *NUV* magnitude of the *GALEX* All-Sky Survey can be used, together with Johnson *BV* magnitudes in a $(NUV-V)_0$ *vs.* $(B-V)_0$ plot, to distinguish blue horizontal branch (BHB) from other A stars of the same $(B-V)$ color for $12<V<18$. In addition, we use SDSS *gr* magnitudes in a $(NUV-r)_0$ *vs.* $(g-r)_0$ plot for $14<r<18$. The faint limit will be extended by $\sim$3 magnitudes for the *GALEX* Medium-Deep Survey. Attempts to use *NUV* in conjunction with 2MASS magnitudes and ROTSE m_r magnitudes did not prove useful. The $(NUV-V)_0$ *vs.* $(B-V)_0$ plot was used to examine BHB star candidates of varying quality near the South Galactic Pole. We conclude that the addition of the *GALEX NUV* significantly adds to the reliabilty with which these stars can be identified.

Subject headings: stars: horizontal branch, Galaxy: structure, Galaxy: halo

1. INTRODUCTION

Blue horizontal branch (BHB) stars together with RR Lyrae stars are the most-used probes of the Galactic halo. BHB stars can be distinguished from other blue stars (e.g. blue stragglers) by the width and shape of their Balmer lines and by the size of their Balmer jump. They have been discovered by using objective-prism spectroscopy (e.g. Sanduleak 1988; Beers et al. 1988; Christlieb et al. 2005) or photoelectric photometry (e.g. Philip 1967; Pier 1982,1983,1984; Sommer-Larsen et al. 1989; Preston et al. 1991; Kinman et al. 1994; Clewley et al. 2004; Sirko et al. 2004; Beers et al. 2007) either alone or in combination with slit spectroscopy. Preston et al. (1991) found that a separation of BHB from other A-stars in a $(U-B)_0$ vs. $(B-V)_0$ plot is only reliable in the color range $-0.03\leq(B-V)_0\leq0.18$ and, because of observational error, the classification is often ambiguous for stars near the ends of this range. Only in this color range can the Balmer jump and the shape and widths of the Balmer lines be used to distinguish the BHB stars (e.g. Clewley et al. 2002). Improved classification can also come from using high S/N high resolution spectra but this has only been achieved so far for the brighter nearby BHB (Kinman et al. 2000; Behr 2003). One can also improve the photometric selection by using more than one photometric system. We here discuss the appropriate colors for identifying BHB stars in a variety of photometric systems with particular reference to the new UV photometry from the Galactic Explorer Satellite (*GALEX*, Martin et al. 2005).

2. THE COLOR WINDOWS FOR BHB STARS USING *GALEX* MAGNITUDES.

2.1. GALEX *and Johnson BV photometry.*

The *GALEX* surveys give a far-UV magnitude (*FUV*) and a near-UV magnitude (*NUV*) at effective wavelengths 1516 and 2267 Å respectively; these are on the *AB* system. These surveys become non-linear for stars brighter than 14 to 15th magnitude (Morrissey et al. 2007), and so require faint BHB stars for calibration. A suitable BHB sample ($11.4<V<16.5$) near the NGP (where the extinction is low) is discussed in Kinman et al. (2007). The coordinates, photometry, radial velocities and abundances of these stars are to be given in T.D. Kinman et al. (2007, in prep.) which will also list the blue non-BHB stars in the same fields. The techniques for selecting these stars are described in Kinman et al. (1994, 1996). Of this NGP sample, 31 BHB stars are in the *GALEX* releases GR2 and GR3, 40 in the SDSS (DR5) survey (York et al. 2000; Adelman-McCarthy et al. 2007) and 15 are in both surveys. Thirty nine non-BHB stars in the same NGP field were also identified in the *GALEX* releases. One BHB star and five non-BHB stars with $NUV\leq14.0$ (corresponding roughly to V = 12.0 for $(B-V)\sim0.0$) were excluded in order to avoid non-linearity effects. *FUV* and *NUV* were corrected for interstellar extinction using A(*FUV*) = 8.16 E$(B-V)$ and A(*NUV*) = 8.90 E$(B-V)$ (Rey et al. 2006); the E$(B-V)$ were taken from Schlegel et al. (1998).

The photometric separation of BHB from other A stars can be achieved by plotting a gravity-sensitive indicator, such as $(U-B)$, against a temperature indicator, such as $(B-V)$. We find that $(NUV-V)_0$ and $(NUV-B)_0$ are effective surrogates for the gravity-sensitive $(U-B)$. All photometric classifications are limited to an effective magnitude range. At the faint end the photometric errors are too large for stars of different types to be separated; at the bright end the detector becomes non-linear. We do not use the *FUV* here because it has a small effective range for stars in the All-Sky Survey (AIS); it may prove useful when the deeper *GALEX* surveys are more complete. $(NUV-V)_0$ and $(NUV-B)_0$ are similar as gravity discriminators but the former includes fewer c-type RR Lyrae stars and was therefore adopted. A plot of $(NUV-V)_0$ *vs.* $(B-V)_0$ (Fig. 1(a)) shows that the BHB stars (filled circles) lie in a compact area (the dotted parallelogram) whereas the non-BHB stars (open circles) largely lie outside this area (Fig. 1(b)). Eight c-type RR Lyrae stars are also shown. We do not know the epochs of the *GALEX* data and so the phases of these variables at the times of their *GALEX* observations are not known. We therefore plotted them both for the case where the variable is at maximum light (filled triangles) and where it is at mean light (open triangles). Confusion of these variables with BHB stars is possible on this plot and so the reddest BHB star candidates should be checked for variability. Most of our *GALEX* data comes from the AIS for which the error in

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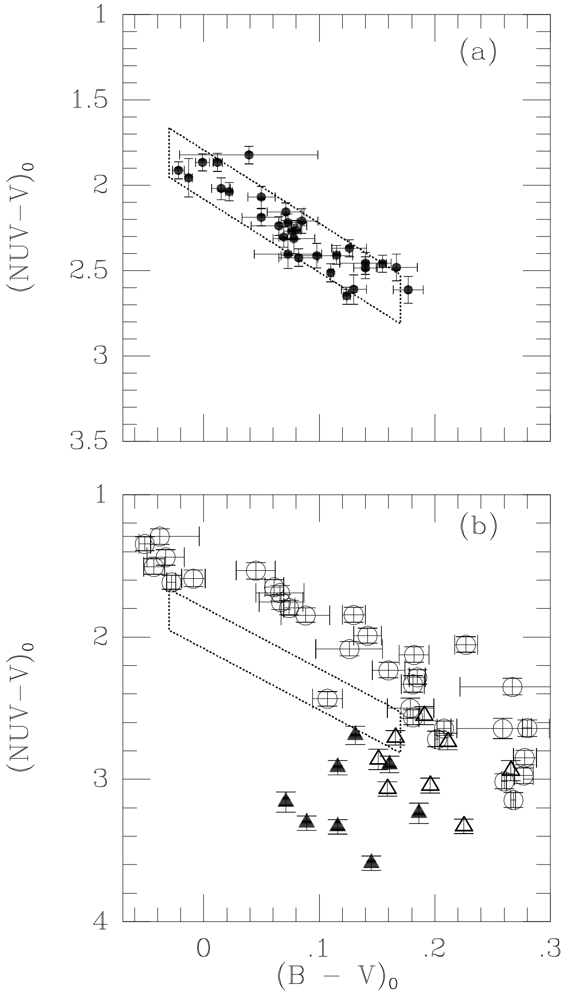

FIG. 1.— $(NUV-V)_0$ *vs.* $(B-V)_0$ for (a) BHB stars (filled circles) and (b) non-BHB stars (open circles) and c-type RR Lyrae stars (open triangles at mean light, filled triangles at maximum light). The $(B-V)_0$, $(NUV-V)_0$ coordinates of the corners of the parallelogram that encloses the BHB stars are: –0.03, 1.665; –0.03, 1.953; +0.17, 2.814; +0.17, 2.526.

$NUV\sim$0.15 mag at NUV = 20.0; the separation of BHB from non-BHB stars will become increasingly inefficient for stars fainter than this. The effective useful range of the AIS data is therefore 14.0$<NUV<$20.0 which corresponds roughly to 12.0$<V<$18.0 for BHB stars. A likely practical use of the $(NUV-V)_0$ *vs.* $(B-V)_0$ plot is to provide improved selection where Johnson photometry is available (e.g. Beers et al. 2007). An example of this is given in Sec 2.4.

2.2. GALEX *and SDSS photometry.*

Sirko et al. (2004) have selected BHB stars in the SDSS system by using a $(u-g)_0$ *vs.* $(g-r)_0$ plot together with spectroscopic criteria. The BHB stars in our NGP sample in the same color plot (Fig 2) lie in the ranges $1.14\leq(u-g)_0\leq1.28$ and $-0.24\leq(g-r)_0\leq-0.04$ (as shown by the box). The color-window ($-0.31\leq(g-r)_0\leq-0.13$) given in Fig. 8 of Sirko et al. (2004) is significantly bluer than this and corresponds roughly to $-0.09\leq(B-V)_0\leq+0.10$. In both cases, however, the region occupied by the BHB stars (filled circles) is heavily contaminated by non-BHB stars (open circles). Fig 3(a) shows the $(u-g)_0$ *vs.* $(g-r)_0$ plot and Fig 3(b) shows the $(NUV-r)_0$ *vs.* $(g-r)_0$ plot (with the same symbols) for the subset of stars in Fig. 2 that have reliable *GALEX* data. The lower contamination of the BHB star region by non-BHB stars in Fig 3(a) compared to Fig 2, may be a fluctuation produced by the smaller number of stars in Fig 3(a) and/or some selection effect produced by the *GALEX* survey itself. The presence of two non-BHB stars (shown as bold open circles) in the BHB star region in both Fig 3(a) and Fig 3(b) suggests an ambiguity in their classification. Otherwise, the use of $(NUV-r)_0$ clearly gives an effective and *independent* method of separating the BHB from non-BHB stars. The use of both SDSS and *GALEX* surveys materially adds to the accuracy of the classification process. Classification should be possible from the *GALEX* AIS survey for stars with 14.2<r<18.0; the bright limit is set by saturation in the SDSS data and the faint limit by the errors in NUV. The use of the *GALEX* Medium-Deep (MIS) survey, which largely overlaps with the SDSS, should extend the faint limit by $\sim$3 mag.

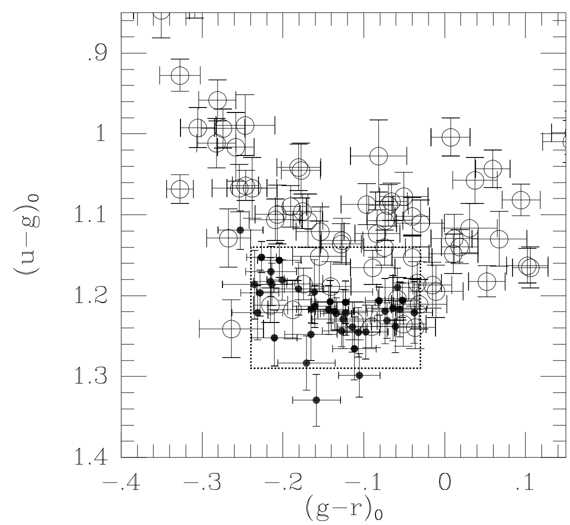

FIG. 2.— $(u-g)_0$ *vs.* $(g-r)_0$ (SDSS colors) for BHB stars (filled circles) and non-BHB stars (open circles). The dotted rectangle encloses the area occupied by the BHB stars.

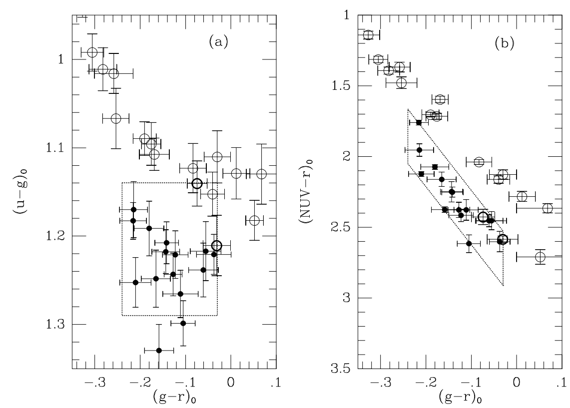

FIG. 3.— (a) $(u-g)_0$ *vs.* $(g-r)_0$ (SDSS colors) and (b) $(NUV-r)$ *vs.* $(g-r)_0$ for stars with GALEX magnitudes (same symbols as Fig. 2). The classification of the two stars with bold ircles is ambiguous from the photometry. The dotted parallelograms enclose the area occupied by the BHB stars. The $(g-r)_0$, $(NUV-r)_0$ coordinates of the corners of the parallelogram in (b) are –0.24, 1.665; –0.24, 2.050; –0.03, 2.911; –0.03, 2.526.

2.3. GALEX *and other photometry.*

It is desirable to find an all-sky survey whose data could be used in conjunction with *GALEX* to identify the brighter BHB stars (V < 14). Brown et al. (2004) suggested that 2MASS data can be used to identify BHB stars in a $(J-H)_0$ *vs.* $(H-K)_0$ plot. Fig 3(a) shows our NGP sample of BHB and non-BHB stars in this plot. It is seen that their color-window (shown by the dotted rectangle) is not optimal and

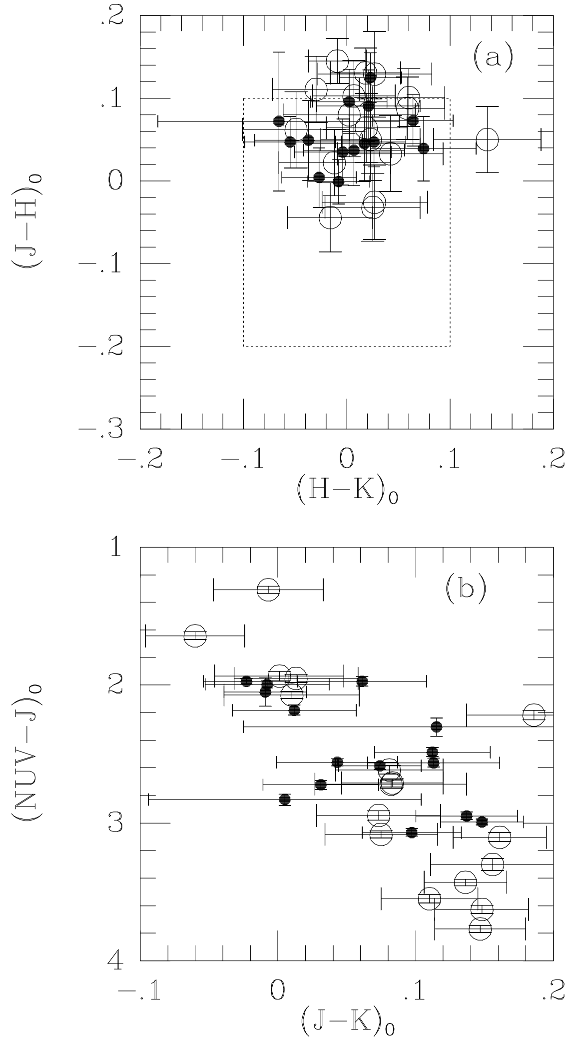

FIG. 4.— (a) 2MASS $(J-H)_0$ *vs.* $(H-K)_0$ for BHB stars (filled circles) and non-BHB stars (open circles) at the NGP. The dotted rectangle shows the selection window used by Brown et al. (2004). (b) $(NUV-J)_0$ *vs.* $(J-K)_0$ for BHB stars (filled circles) and non-BHB stars (open circles) at the NGP.

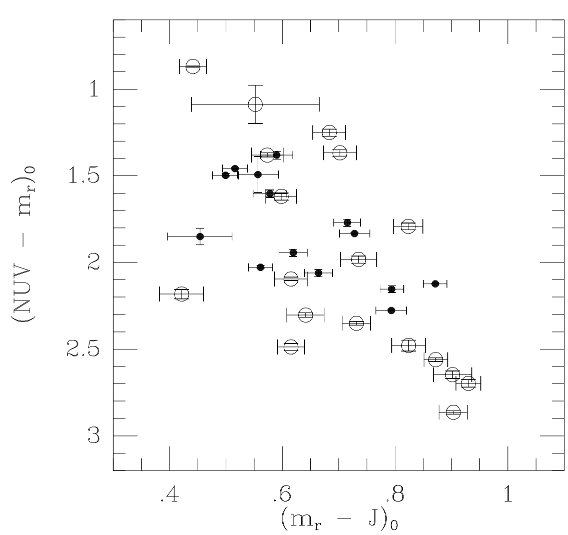

FIG. 5.— $(NUV-m_r)_0$ *vs.* $(m_r-J)_0$ where *NUV* is from *GALEX*, J from 2MASS and m_r is from the NSVS. The filled and open circles show BHB and non-BHB stars respectively from the NGP field.

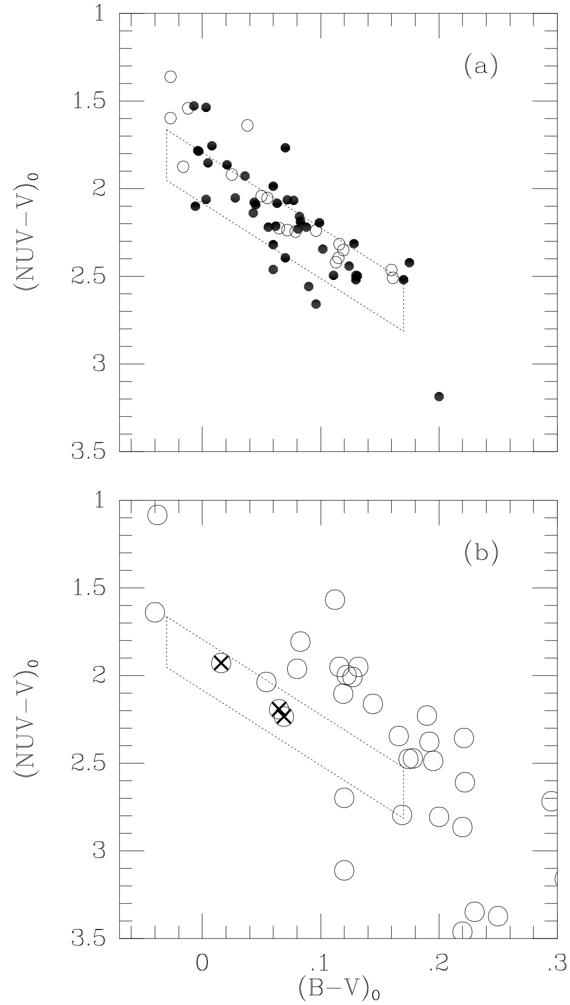

FIG. 6.— $(NUV-V)_0$ *vs.* $(B-V)_0$ for (a) Most likely (filled circles) and quite likely (small open circles) BHB star candidates near the SGP. (b) Least likely candidates shown as large open circles. The dotted rectangle is that which encloses the BHB stars in a similar plot for the NGP BHB stars. The crosses are explained in the text.

that there is little separation between the two types of star. It is found (Fig 3(b)) that the $(NUV-J)_0$ *vs.* $(J-K)_0$ plot is also ineffective since $(NUV-J)_0$ is not a possible gravity indicator. This is also true of $(NUV-m_r)$ (where m_r is the unfiltered CCD magnitude of the Northern Sky Variability Survey (NSVS) (Wozniak et al. 2004))[3]. Fig 4 shows the plot of $(NUV-m_r)$ *vs.* (m_r-J) for our NGP stars; only a weak separation between the BHB and non-BHB stars is seen (probably because m_r has such a broad bandwidth). The V magnitudes of the All Sky Automatic Survey (ASAS) (Pojmanski 2002) are available for declinations South of +28°, but the magnitude range in which both these V and NUV are accurate is rather limited. Apart from this, therefore, there does not seem to be a way of identifying the brighter BHB stars in currently published wide-field surveys.

2.4. GALEX *and a sample at the South Galactic Pole (SGP).*

An (unpublished) catalog of BHB candidates within 10° of the SGP has been compiled from various sources (e.g. Christlieb et al. 2005; Beers et al. 1988; Lance, 1988). The data is of varying accuracy and (largely from their UBV colors) they were judged to be (a) most likely (b) quite likely (c)

[3] This survey covers the sky North of declination −38°.

not likely to be BHB stars. The first two classes are shown by filled and small open circles respectively in the plot of $(NUV-V)_0$ *vs.* $(B-V)_0$ (Fig. 5(a)) where the dotted rectangle is that which encloses the NGP BHB stars in Fig 1(a). The difference between the distributions of the filled and open circles is not marked and with the exception of a few outliers, most of these stars probably are BHB stars. We suspect that the scatter is largely caused by the (unknown) errors in $(B-V)_0$ in this heterogeneous data. There may also be systematic differences between the Northern and the Southern hemisphere photometry standards that affect $(B-V)_0$ (Menzies et al. 1991). The classification of the outliers in this plot therefore requires an assesment of the likely errors in each $(B-V)_0$ and this is beyond the scope of this Letter. A similar plot for the SGP stars that were judged least likely to be BHB stars is shown in Fig 5(b). A few lie inside the rectangle that encloses the NGP BHB stars. The three marked with crosses are BPS CS 22882-32 and BPS CS 22942-34 whose radial velocities are +98 and +192 km s^{-1} (Pier 1983) respectively and PS 2-58 whose radial velocity is +200 km s^{-1} (Rodgers 1971); these high radial velocities also support the classification of these stars as BHB stars. The efficiency in separating BHB stars from their interlopers using plots such as $(NUV-V)_0$ *vs.* $(B-V)_0$ is dependent on the accuracy of the color used as the temperature indicator. Consequently, it would be advantageous to use a temperature indicator that combines the information from all the optical and infrared magnitudes that are available.

3. SUMMARY

It is shown that the *GALEX NUV* magnitude can be used in conjunction with Johnson *BV* magnitudes in a $(NUV-V)_0$ *vs.* $(B-V)_0$ plot to distinguish BHB from other A stars of the same $(B-V)$ color. A similar separation can made using *NUV* and the SDSS *gr* magnitudes in a $(NUV-r)_0$ *vs.* $(g-r)_0$ plot. These plots are effective for stars in the *GALEX* AIS in the magnitude ranges $12<V<18$ and $14<r<18$ for Johnson and SDSS colors respectively. The faint limit is $\sim$3 magnitudes fainter for the *GALEX* Medium-Deep Survey. The bright limit is set by the onset of non-linearity in the *GALEX* detector in the case of the Johnson colors and by the saturation of the SDSS detectors in their case. Attempts to use *NUV* in conjunction with 2MASS magnitudes and ROTSE m_r magnitudes to separate BHB from non-BHB stars were not successful. The $(NUV-V)_0$ *vs.* $(B-V)_0$ plot was used to confirm BHB star candidates of varying quality near the South Galactic Pole. It is concluded that the addition of the *GALEX NUV* to existing data gives a simple and powerful way of identifying these stars.

We thank Heather Morrison for help in selecting SDSS stars. We acknowledge NASA's support for the *GALEX* mission. Funding for SDSS has been provided by the Alfred P. Sloan Foundation, the Participating Institutions, NSF, DoE, NASA, Monbukagakusho, and the Max Planck Society. This publication makes use of 2MASS, which is a joint project of the University of Massachusetts and the IPAC/Caltech, funded by NASA and NSF. Finally, we thank the referee for suggestions which materially clarified parts of the paper.

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